Mars Ascent on a Small Scale: Propulsion Hardware Options

One of NASA's most ambitious stated goals over the next decade is to return soil and rock samples from Mars to earth. This must be accomplished with Delta-class missions since funding constraints are expected to prohibit Titan-class exploration for the forseeab e future. However the design of sufficiently lightweight propulsion hardware, for launching an affordably-small return vehicle from Mars, has received scant attention in the technical literature. Therefore, this paper addresses propulsion hardware options for Mars ascent vehicles in the range 100 kg to 1000 kg. This is a separate issue from research into the production of propellants on Mars, which has been well-represented in the literature.

Transporting a sample from the surface of Mars to earth requires a very high performance maneuver having a total velocity change (Δv) above 6000 m/s. Launching from the surface into a low Mars orbit requires most of this Δv (~4000 m/s) at an initial acceleration close to 1 g (earth gravity). Even this initial part of the journey presents a greater propulsion challenge than any spacecraft engineering team has successfully faced to date. Figure 1 compares the Δv and acceleration requirements of Mars launch to that of other missions. Clearly, the only solved propulsion problem which has a more difficult combination of Δv and acceleration is earth launch itself, which has not been done on a miniature scale.

Since space maneuvers performed to date require relatively less performance, propulsion technology needed for small scale (<1000 kg at launch) Mars sample return vehicles does not currently exist. The Mars ascent vehicle must essentially be one or more miniature launcher stages. However, the difficulty of creating arbitrarily small upper stages is a strong constraint which offsets the benefits of staging for the smallest systems. It is therefore proposed that the first stage must at least reach a low Mars orbit.

This paper considers two major areas for improvement over conventional spacecraft propulsion methodologies. Firstly, a Mars mini-launcher must be configured to have an absolute minimum of non-tankage structure, just as earth launch vehicles do. Secondly, the value of using pump-fed operation instead of a pressure-fed propulsion system is considered. Several options each for vehicle packaging and pump-fed operation are presented and discussed.

A major packaging constraint is the need for a shape which fits within an aeroshell for atmospheric entry and descent at Mars. Therefore, the Mars mini-launcher cannot take advantage of long stacked cylindrical tanks as earth launcher stages do. Instead, a unique common-bulkhead tank configuration is proposed, having an aspect ratio near 1:1. The reduced requirements for insulation and non-tankage structure are compared to those of the more conventional 4-tank biprop configuration (used on Apollo modules, for example).

Pump-fed operation enables the use of low-pressure tanks and high pressure thrust chambers, which respectively can reduce the weight of these major components. However, Figure 2 shows that pump weight does not scale down with thrust level, for conventional turbopumps. Over the thrust range required by Mars launchers on the scale of interest, reciprocating pumps offer a potentially lighter alternative. The development history of rocket propulsion with reciprocating pumps is therefore reviewed. New concepts for pump-fed bipropellant engine cycles between 100 lb and 2000 lb of thrust are discussed in the context of the Mars ascent problem.

For each propulsion option under consideration, the masses of major hardware components are carefully documented and compared among the various options. For example, conventional spacecraft tank and engine technologies are summarized graphically, in terms of nondimensionalized hardware weights as a function of scale. The masses of nonconventional propulsion components are derived from stress analysis and also based on experimental hardware. As one example, issues related to the feasibility of low-pressure tanks (e.g. wall thickness lower limits) for pump-fed systems are addressed. Figure 3 compares the mass budgets of a number of propulsion alternatives, for a 100 kg Mars mini-launcher.

The paper suggests that a pump-fed mini-launcher can be mission enabling for the smallest scale Mars sample return missions. Such a new propulsion capability would have additional applications, in GTO-GEO apogee maneuvers, and in upper stages for small earth launchers tailored for microspacecraft. Recommendations are made as to what development paths should be attempted, and in what priority, in order to establish concept viability as early as possible and to arrive at a cost-effective solution for a miniature Mars launch vehicle. A cost comparison is made between propulsion R&D and the avoided cost of using a heavy-lift earth launch vehicle to support larger-scale Mars sample return missions.

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